The Coming Revolutions in Particle Physics

Chris Quigg
Fermilab

Fermilab Colloquium · April 28, 2004

Lectures/Readings

The Coming Revolutions in Particle Physics

Chris Quigg, Fermilab

Wonderful opportunities await particle physics over the next decade, with new instruments and experiments poised to explore the frontiers of high energy, infinitesimal distances, and exquisite rarity. We look forward to the Large Hadron Collider at CERN to explore the 1-TeV scale (extending efforts at LEP and the Tevatron to unravel the nature of electroweak symmetry breaking) and many initiatives to develop our understanding of the problem of identity: what makes a neutrino a neutrino and a top quark a top quark. We suspect that the detection of proton decay is only a few orders of magnitude away in sensitivity. Astronomical observations should help to tell us what kinds of matter and energy make up the universe. We might even learn to read experiment for clues about the dimensionality of spacetime. If we are inventive enough, we may be able to follow this rich menu with the physics opportunities offered by a linear electron-positron collider and a (muon storage ring) neutrino factory. I expect a remarkable flowering of experimental particle physics, and of theoretical physics that engages with experiment.

• For more events, browse the Academy Events database.

Event Information

Apr 28, 2004
4:00 PM
Fermi National Accelerator Laboratory, Batavia, IL
Map & Directions

Main
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- Conferences/Meetings
- Radio
- Television/Film
- Kids & Family Events
- Education Programs
- Performance
- Exhibits/Tours
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April

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4	5	6	7	8	9	10
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18	19	20	21	22	23	24
25	26	27	28	29	30	

May

S	M	T	W	T	F	S

Galileo's Three Revolutions

Eppur si muove . . .

▷ Completing the Copernican Revolution
Humans do not occupy a privileged location in the Universe

Cimenti . . .

▷ Rejecting Authority:
Learning to read Nature by doing experiments

The minute particular . . .

▷ Not asking general questions and receiving limited answers,
but asking limited questions and finding general answers

Io stimo più il trovar un vero, benchè di cosa leggiera, ch'l disputar lungamente delle massime questioni senza conseguir verità nissuna.

The Great Lesson of Twentieth-Century Science

The human scale of space & time

is not privileged for understanding Nature . . .

and may even be disadvantaged

From the 1898–99 University of Chicago catalogue:

"While it is never safe to affirm that the future of the Physical Sciences has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice . . . . An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals."

A Decade of Discovery Past . . .

- ▷ Electroweak theory $\longrightarrow$ law of nature
- ▷ Higgs-boson influence observed in the vacuum
- ▷ Neutrino flavor oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$
- ▷ Understanding QCD
- ▷ Discovery of top quark
- ▷ Direct CP violation in $K \to \pi\pi$ decay
- ▷ B-meson decays violate CP
- ▷ Flat universe dominated by dark matter & energy
- ▷ Detection of ν_τ interactions
- ▷ Quarks & leptons structureless at TeV scale

A Decade of Discovery Past . . .

- ▷ Electroweak theory $\longrightarrow$ law of nature $[Z,\, e^+e^-,\, \bar{p}p,\, \nu N,\, (g-2)_\mu,\, \ldots]$
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \to \nu_\tau,\, \nu_e \to \nu_\mu/\nu_\tau$ [$\nu_\odot,\, \nu_{\mathrm{atm}}$]
- ▷ Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct CP violation in $K \to \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate CP [$e^+e^- \to B\bar{B}$]
- ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

A Decade of Discovery Past . . .

- ▷ $\boxed{\text{Electroweak theory} \to \text{law of nature}}$ [Z, e^+e^-, $\bar{p}p$, νN, $(g-2)_\mu$, . . .]
- ▷ $\boxed{\text{Higgs-boson influence observed in the vacuum}}$ [EW experiments]
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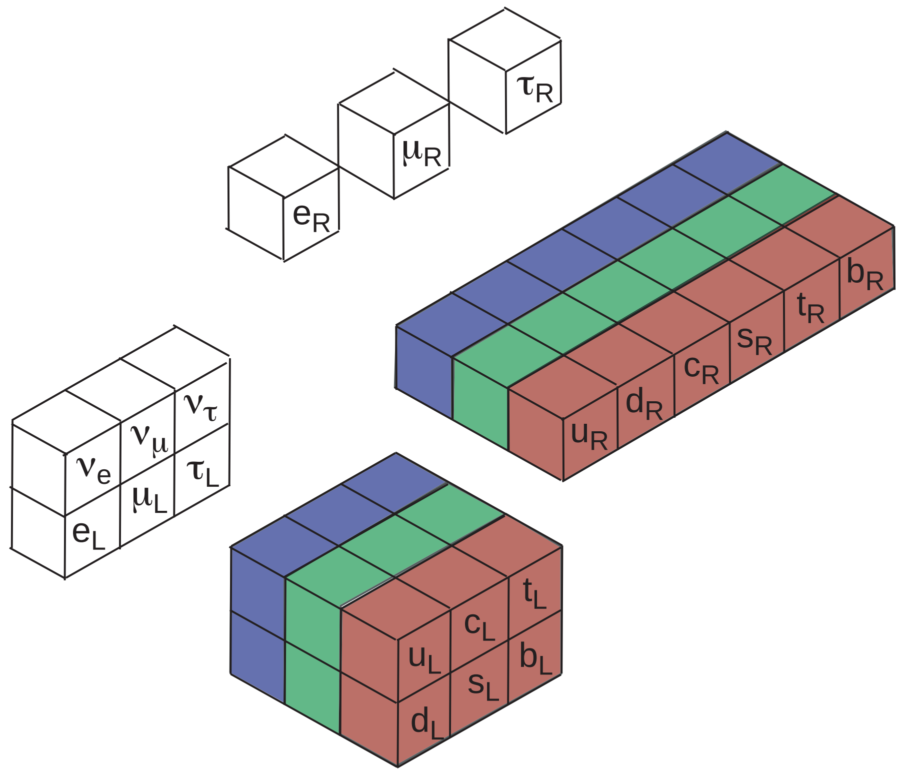
- ▷ $\boxed{\text{Quarks \& leptons structureless at TeV scale}}$ [mainly colliders]

Our Picture of Matter (the Revolution Just Past)

Pointlike ($r \lesssim 10^{-18}$ m) **quarks and leptons**



with interactions specified by

$$\mathbf{SU(3)_c} \otimes \mathbf{SU(2)}_L \otimes \mathbf{U(1)}_Y$$

gauge symmetries . . .

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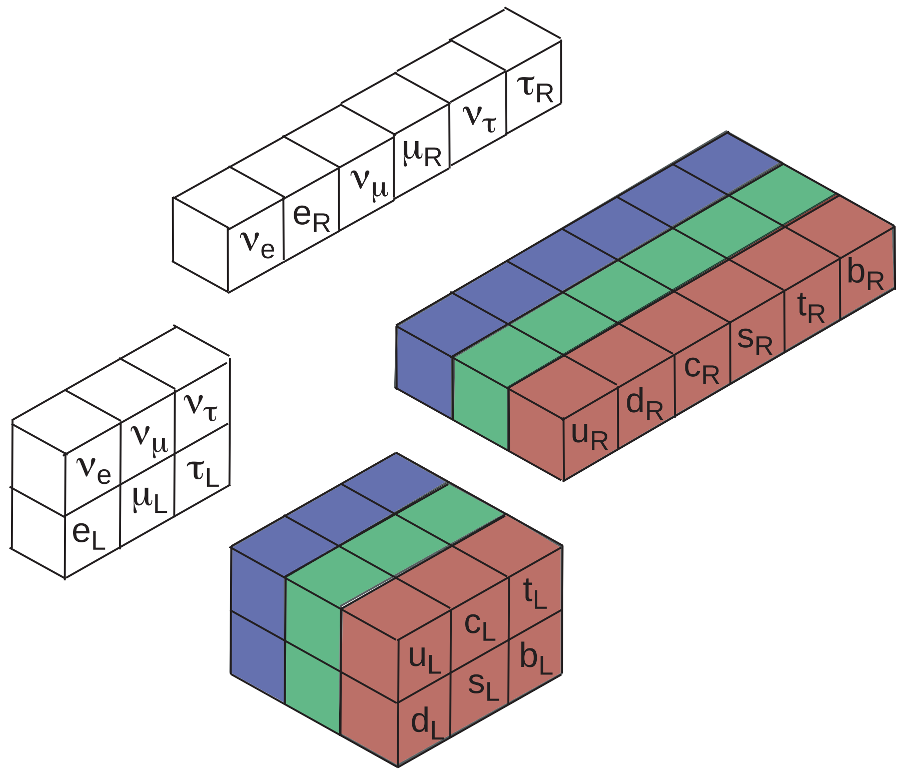

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gauge symmetries . . .

The World's Most Powerful Microscope

Fermilab's Tevatron Collider & Detectors

900-GeV protons: $c - 586$ km/h

980-GeV protons: $c - 495$ km/h

Improvement: 91 km/h!

Protons, antiprotons pass my window 45 000 times per second

...working toward $20\times$ increase in luminosity

$\Rightarrow 10^7$ collisions / second

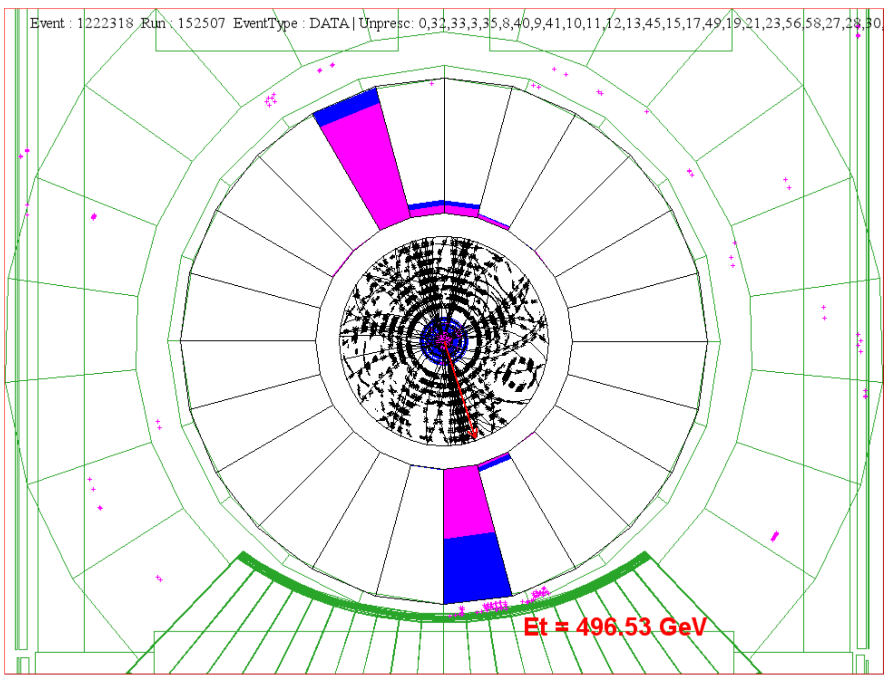
Large Hadron Collider at CERN, 7-TeV protons: $c - 10$ km/h

Run 152507 event 1222318

Dijet Mass = 1364 GeV (corr)

cos θ^* = 0.30

z vertex = -25 cm

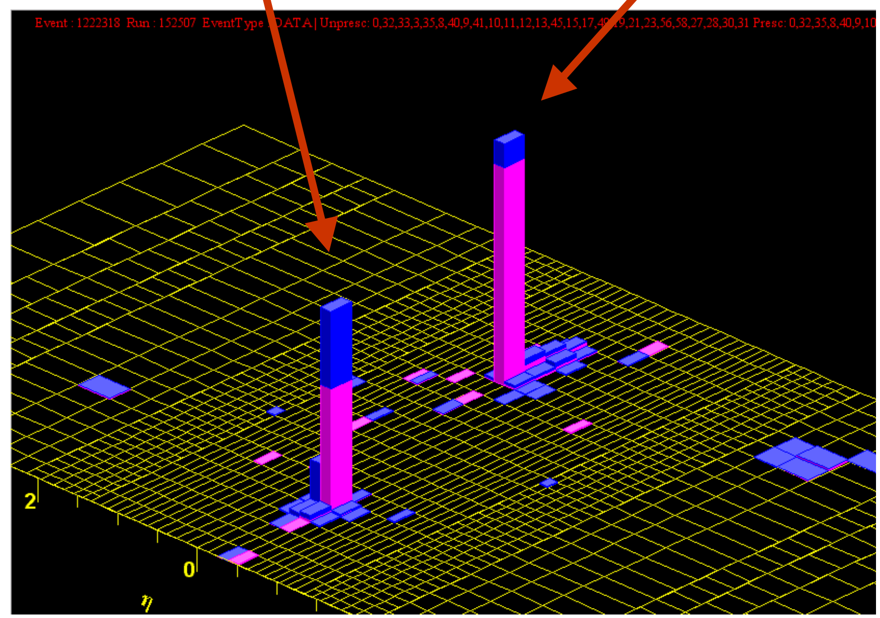


J2 E_T = 633 GeV (corr)
546 GeV (raw)

J2 η = -0.30 (detector)
= -0.19 (correct z)

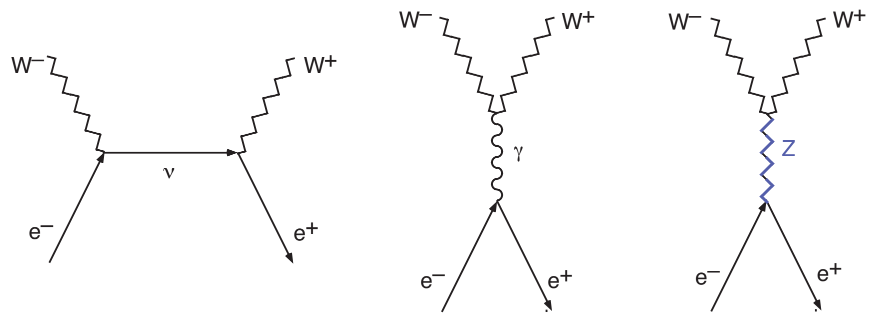
J1 E_T = 666 GeV (corr)
583 GeV (raw)

J1 η = 0.31 (detector)
= 0.43 (correct z)



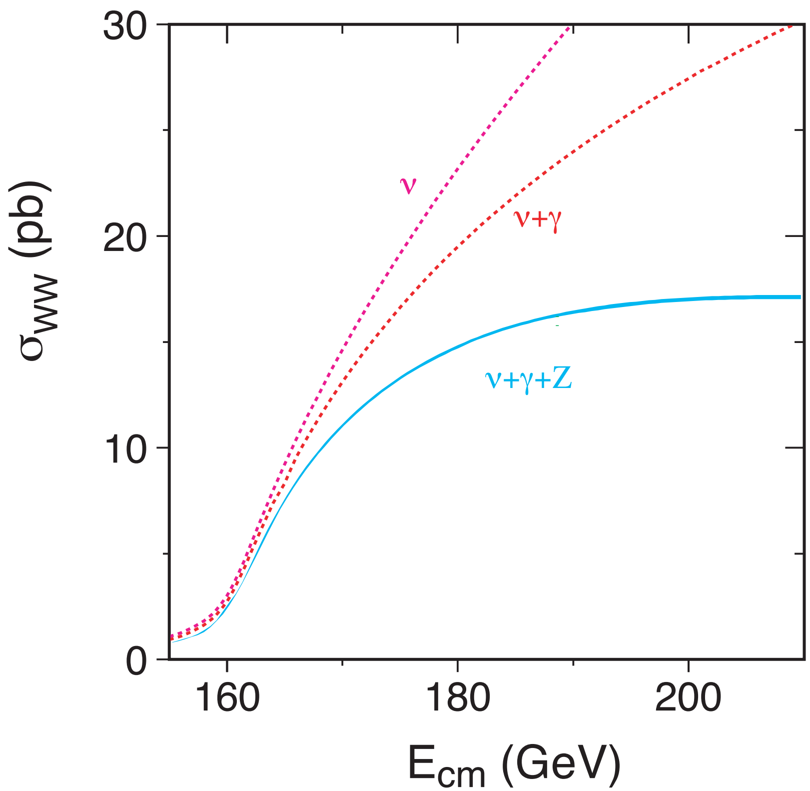
CDF Run 2 Preliminary

Gauge symmetry (group-theory structure) tested in $e^+e^- \to W^+W^-$



each grows unacceptably . . .

but the sum
is well-behaved



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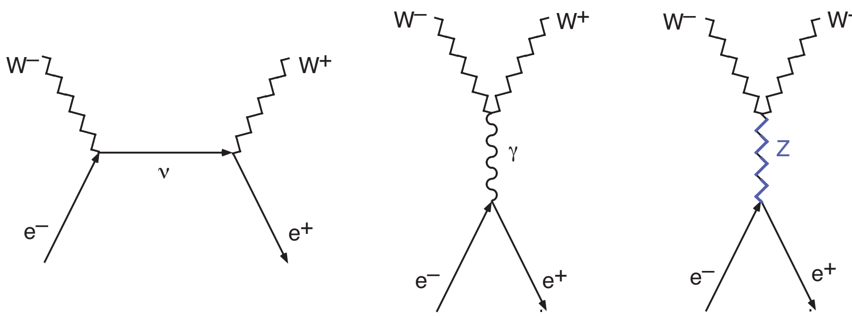

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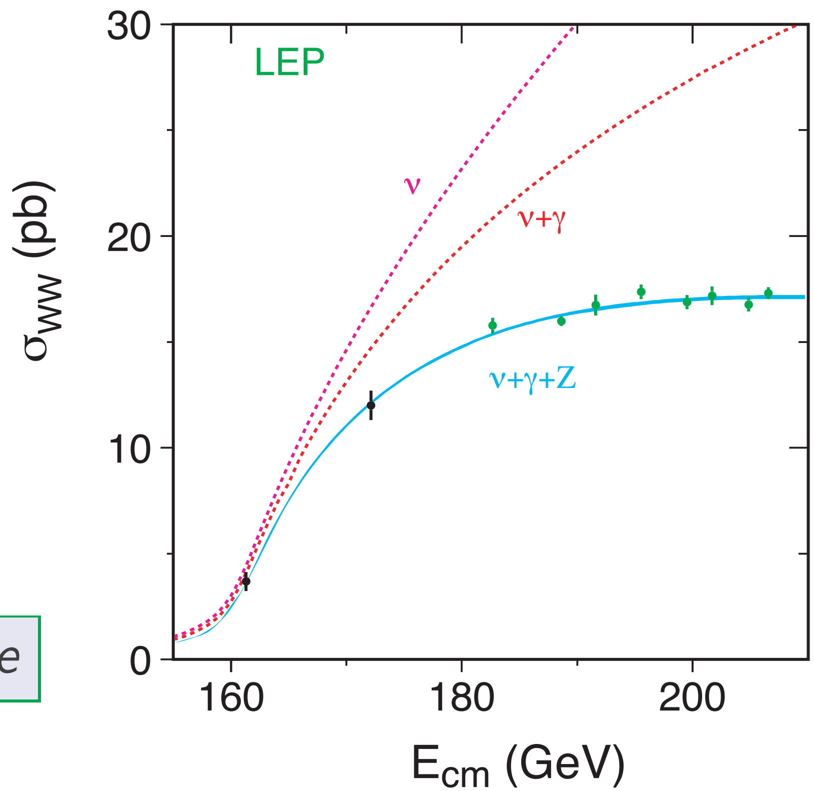


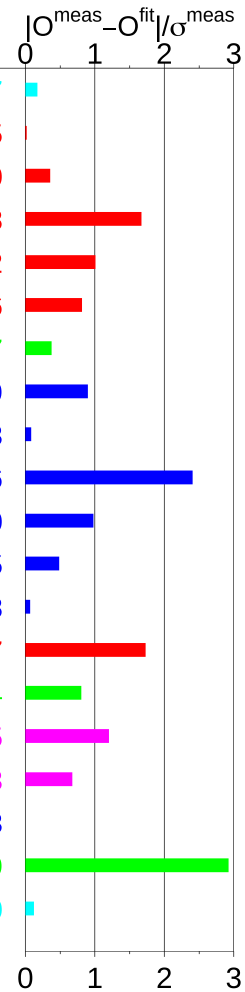
. . . and describes Nature!

New physics on TeV scale

Precision measurements test the theory . . .

Summer 2003

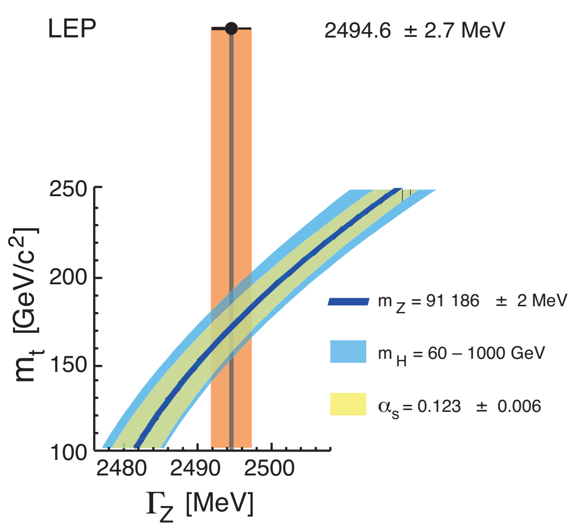
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90

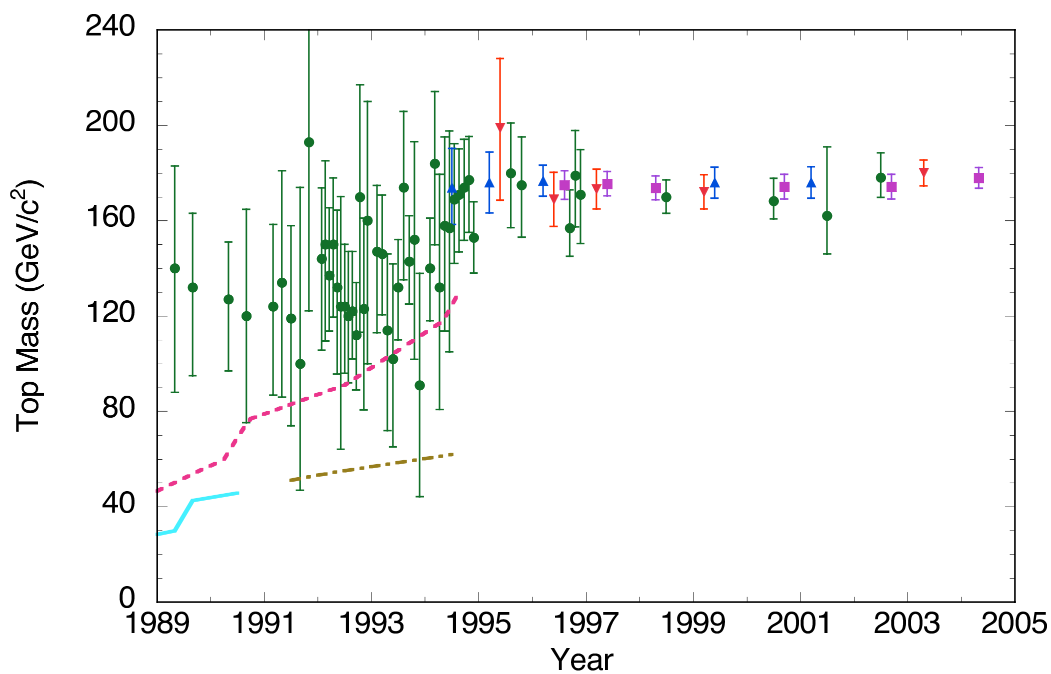


LEP Electroweak Working Group

Precision measurements determine unknown parameters . . .

Infer top mass through quantum corrections:





Revolution:

Understanding the Everyday

- Why are there atoms?
- Why chemistry?
- Why stable structures?
- What makes life possible?

If electroweak symmetry were not hidden . . .

- ▷ Quarks and leptons would remain massless
- ▷ QCD would confine them into color-singlet hadrons
- ▷ Nucleon mass would be little changed, but proton outweighs neutron
- ▷ QCD breaks EW symmetry, gives $(1/2500\times)$ observed masses to W, Z
- ▷ Rapid! β-decay $\Rightarrow$ lightest nucleus is one neutron; no hydrogen atom
- ▷ Probably some light elements in BBN, but ∞ Bohr radius
- ▷ No atoms (as we know them) means no chemistry, no stable composite structures like the solids and liquids we know

. . . the character of the physical world would be profoundly changed

Searching for the mechanism of electroweak symmetry breaking, we seek to understand

why the world is the way it is.

This is one of the deepest questions humans have ever pursued, and

it is coming within the reach of particle physics.

The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV.

We do not know the nature of the new force.

What is the nature of the mysterious new force that hides electroweak symmetry?

▷ A fundamental force of a new character, based on interactions of an elementary scalar

▷ A new gauge force, perhaps acting on undiscovered constituents

▷ A residual force that emerges from strong dynamics among the weak gauge bosons

▷ An echo of extra spacetime dimensions

Which path has Nature taken?

Essential step toward understanding the new force that shapes our world:

find the Higgs boson and explore its properties.

- ▷ Is it there? How many?
- ▷ Verify $J^{PC} = 0^{++}$
- ▷ Does H generate mass for gauge bosons, fermions?
- ▷ How does H interact with itself?

$\boxed{\textit{Finding the Higgs boson starts a new adventure!}}$

Revolution:

The Meaning of Identity

Varieties of Matter

▷ What sets masses & mixings of quarks & leptons?

▷ What is $\mathcal{CP}$ violation trying to tell us?

▷ Neutrino oscillations give us another take, might hold a key to the matter excess in the universe.

$\boxed{\text{All fermion masses and mixings mean new physics}}$

▷ Will new kinds of matter help us see the pattern?
sterile neutrinos, superpartners, dark matter . . .

Many extensions to EW theory entail dark matter candidates.

Supersymmetry is highly developed, and has several important consequences:

- ▷ Predicts that the Higgs field condenses (breaking EW symmetry), if the top quark is heavy
- ▷ Predicts a light Higgs mass
- ▷ Predicts cosmological cold dark matter
- ▷ In a unified theory, explains the values of the standard-model coupling constants

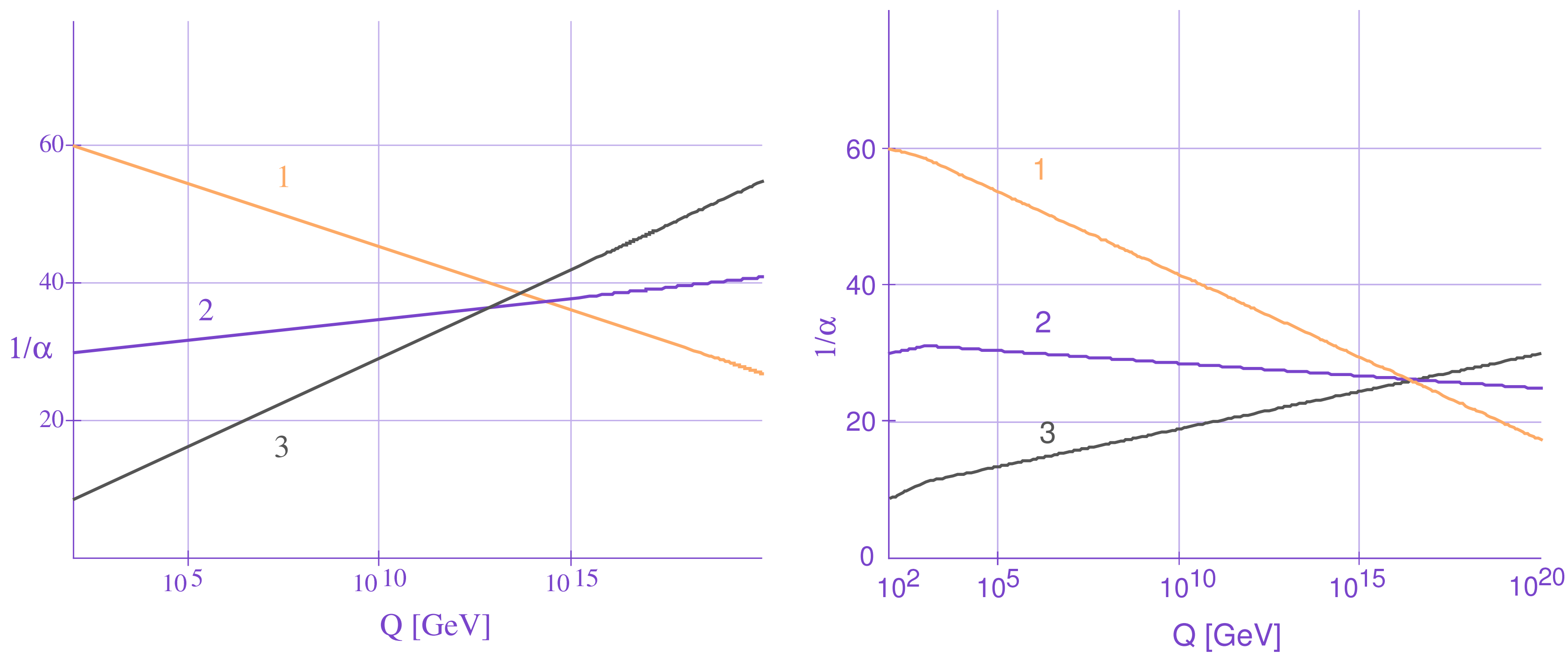
Revolution:

The Unity of Quarks & Leptons

- ▷ What do quarks and leptons have in common?
- ▷ Why are atoms so remarkably neutral?
- ▷ Which quarks go with which leptons?
- ▷ Quark-lepton extended family $\rightsquigarrow$ proton decay:

SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y

- ▷ Unified theories $\rightsquigarrow$ coupling constant unification
- ▷ Rational fermion mass pattern at high energy?



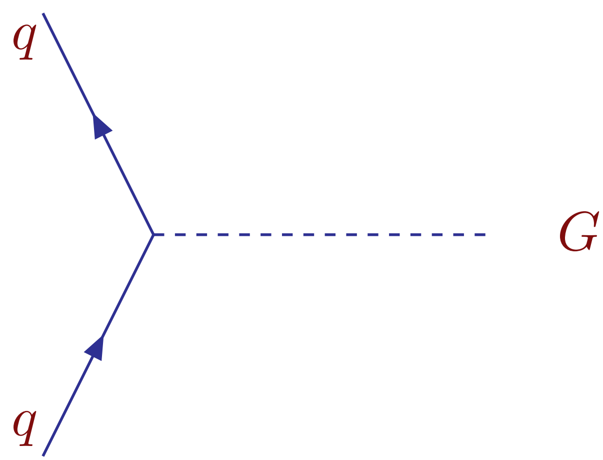
60
40
20
1/α
1
2
3
10^5
10^{10}
10^{15}
Q [GeV]
60
40
20
0
1/α
1
2
3
10^2
10^5
10^{10}
10^{15}
10^{20}
Q [GeV]

Revolution:

Gravity rejoins Particle Physics rejoins

Natural to neglect gravity in particle physics

$$G_{\text{Newton}}\ \textit{small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19}\ \text{GeV}\ \textit{large}$$

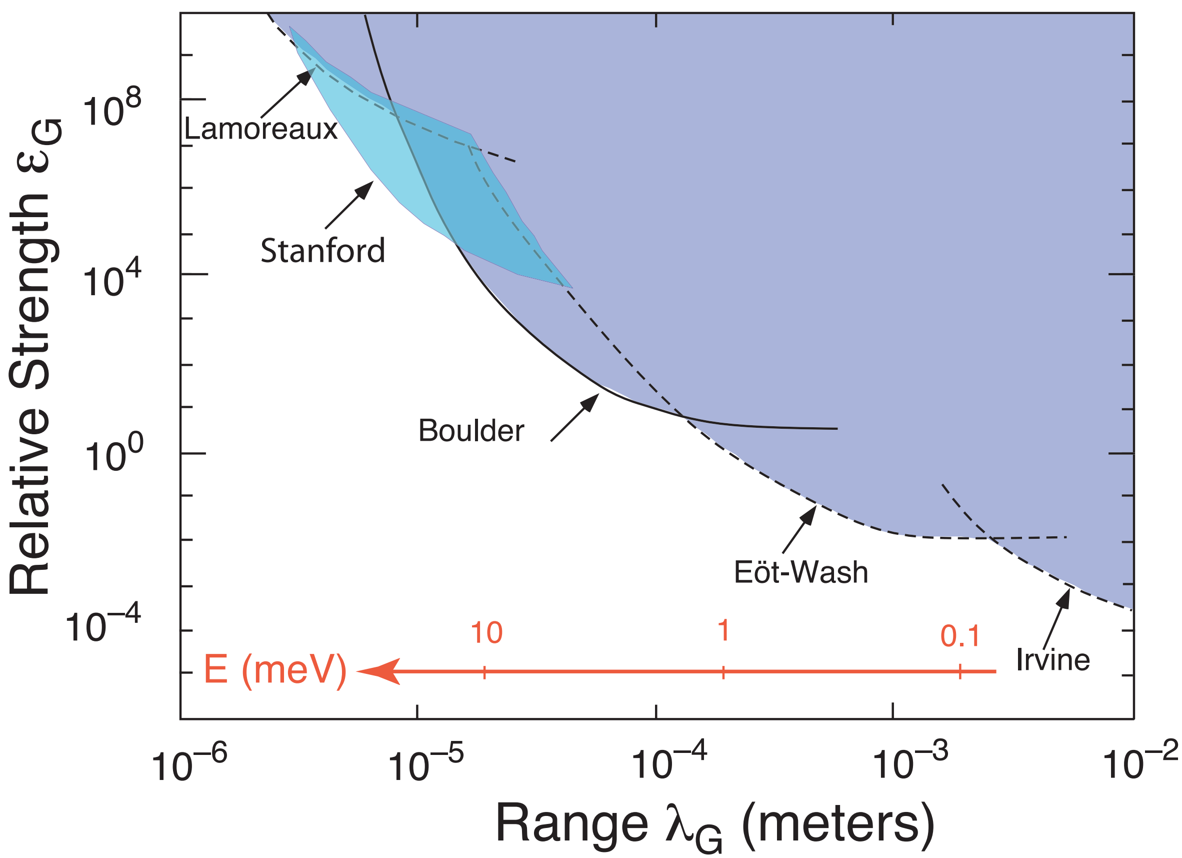


$$\sim \frac{E}{M_{\text{Planck}}}$$

$$\text{Estimate } B(K \to \pi G) \sim \left(\frac{M_K}{M_{\text{Planck}}}\right)^2 \sim 10^{-38}$$

Gravity follows Newtonian force law down to $\lesssim 1$ mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\mathsf{Newton}}\rho(r_1)\rho(r_2)}{r_{12}} \left[1 + \varepsilon_{\mathrm{G}} \exp(-r_{12}/\lambda_{\mathrm{G}})\right]$$



(long-distance alternatives to dark matter)

But gravity is not always negligible . . .

Higgs potential $V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|(\varphi^\dagger\varphi)^2$

At the minimum,

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda| v^4}{4} < 0.$$

Identify $M_H^2 = -2\mu^2$

contributes field-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8}}$$

Adding vacuum energy density $\varrho_{\text{vac}} \Leftrightarrow$ adding cosmological constant Λ to Einstein's equation

$$R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu} = \frac{8\pi G_{\text{Newton}}}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu} \qquad \Lambda = \frac{8\pi G_{\text{Newton}}}{c^4} \varrho_{\text{vac}}$$

observed vacuum energy density $\varrho_{\text{vac}} \lesssim 10^{-46}$ GeV^4

≈ 10 MeV/ ℓ or 10^{-29} g cm^{-3}

But $M_H \gtrsim 114$ GeV $\Rightarrow$

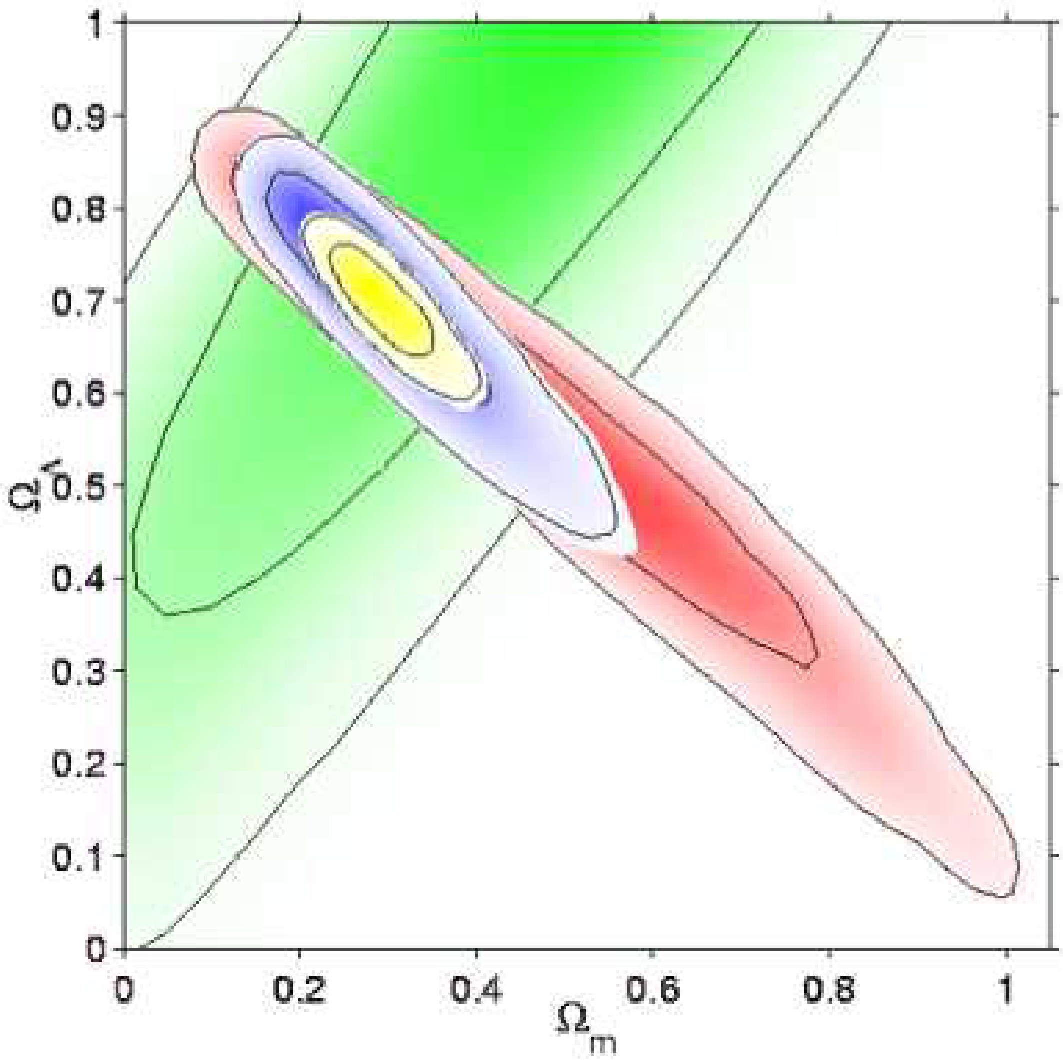
$$\varrho_H \gtrsim 10^8 \text{ GeV}^4$$

MISMATCH BY 54 ORDERS OR MAGNITUDE

A chronic dull headache for thirty years . . .

Why is empty space so nearly massless?

Evidence that vacuum energy is present . . .



. . . recasts the old problem and gives us properties to measure

How to separate EW scale from higher scales?

Conventional approach: change electroweak theory to understand

$$\boxed{\text{why } M_H\text{, electroweak scale} \ll M_{\text{Planck}}}$$

To resolve the hierarchy problem: *extend the standard model*

$$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \left\{ \begin{array}{c} \text{composite Higgs boson} \\ \text{technicolor / topcolor} \\ \text{supersymmetry} \\ \ldots \end{array} \right.$$

Newer approach: ask why gravity is so weak

$$\boxed{\text{why } M_{\text{Planck}} \gg \text{electroweak scale}}$$

Revolution:

A New Conception of Spacetime

Revolution:

A New Conception of Spacetime

- ▷ Could there be more space dimensions than we have perceived?
- ▷ What is their size?
- ▷ What is their shape?
- ▷ How do they influence the world?
- ▷ How can we map them?

9 or 10 needed for consistency of string theory

Suppose at scale R . . . Gravity propagates in $4+n$ dimensions

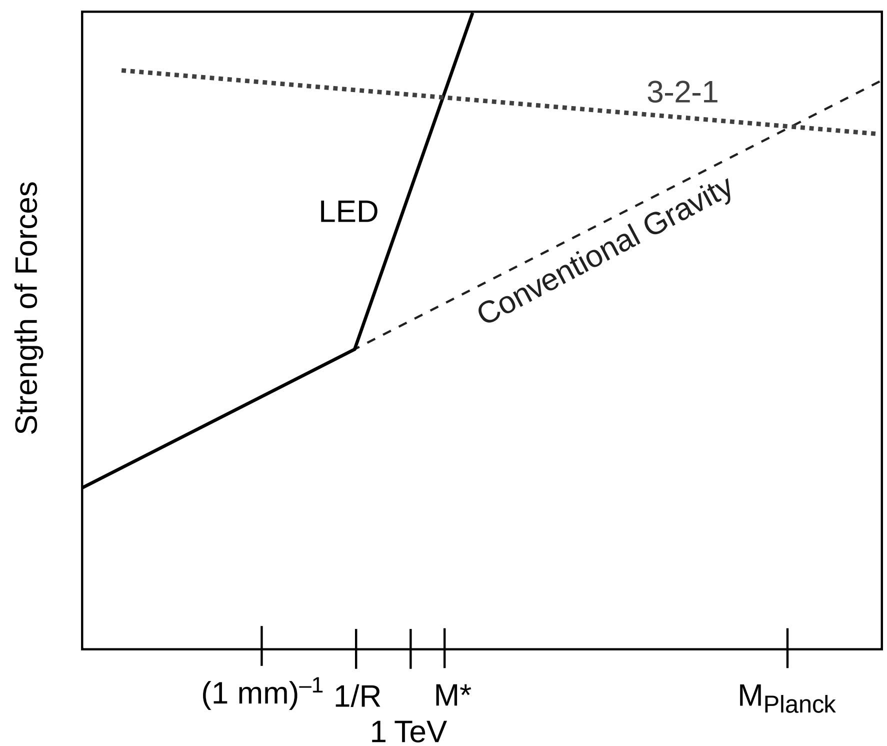
Force law changes:

Gauss's law $\Rightarrow$ $G_{\mathrm{N}} \sim M_{\mathrm{Pl}}^{-2} \sim M^{\star\,-n-2} R^{-n}$ $M^{\star}$: gravity's true scale

Example: $M^{\star} = 1$ TeV $\Rightarrow R \lesssim 10^{-3}$ m for $n = 2$

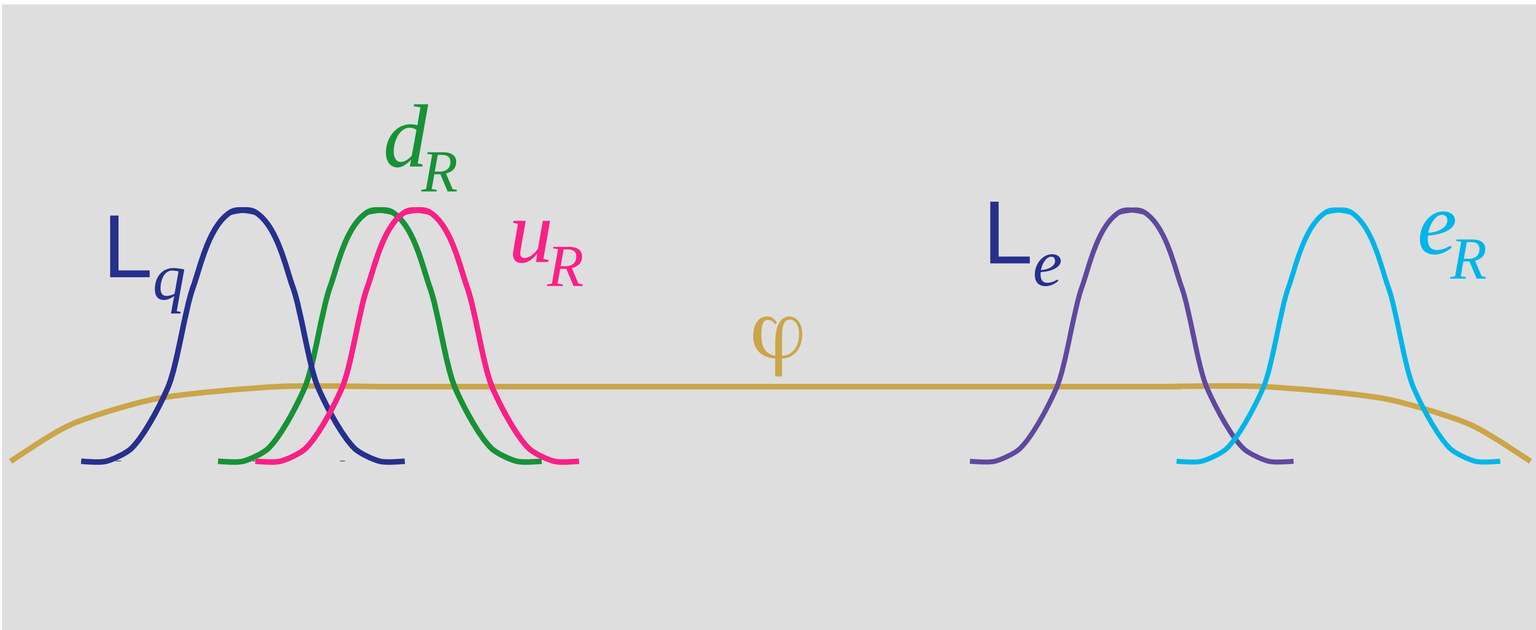
Traditional: Use 4-d force law to extrapolate gravity to higher energies; M_{P} $\sim$ scale where Gravity, SM forces are of comparable strength

IF Gravity probes extra dimensions for $E \lesssim 1/R$, Gravity meets other forces at $E = M^{\star} \ll M_{\mathrm{P}}$



$\boxed{M_{\mathrm{P}} \text{ is a mirage (false extrapolation)!}}$

Might Extra Dimensions Explain the Range of Fermion Masses?



Different fermions ride different tracks in the fifth dimension

Small offsets in the new coordinate $\Rightarrow$ exponential differences in masses

Other extradimensional delights . . .

(provided gravity is intrinsically strong)

▷ If the size of extra dimensions is close to 10^{-19} m, tiny black holes might be formed in high-energy collisions: explosive evaporation $\Rightarrow$ collider hedgehogs, spectacular UHECR showers

▷ Collider experiments can detect graviton radiation (missing-energy signatures) or graviton exchange (angular distributions)

(Cf. Dyson v. Greene)

Gravity is here to stay!

Need to Prepare Many Revolutions!

- Experiments at the energy frontier
- Experiments at high sensitivity
- Fundamental physics with “found beams”
- Astrophysical observations
- The importance of scale diversity for a healthy and productive future

The most ambitious accelerators are major drivers of our scientific progress

Refine e, p technologies · Exotic technologies · Exotic particles

A Decade of Discovery Ahead . . .

- ▷ Higgs search and study; EWSB / 1-TeV scale
- ▷ CP violation (B); Rare decays (K, D, . . .)
- ▷ Neutrino oscillations
- ▷ Top as a tool
- ▷ New phases of matter; hadronic physics
- ▷ Exploration!
  Extra dimensions / new dynamics / SUSY / new forces & constituents
- ▷ Proton decay
- ▷ Composition of the universe

A Decade of Discovery Ahead . . .

- ▷ Higgs search and study; EWSB / 1-TeV scale [$p^{\pm}p$ colliders; e^+e^- LC]
- ▷ CP violation (B); Rare decays (K, D, . . .) [e^+e^-, $p^{\pm}p$, fixed-target]
- ▷ Neutrino oscillations [$\nu_{\odot}$, ν_{atm}, reactors, ν beams]
- ▷ Top as a tool [$p^{\pm}p$ colliders; e^+e^- LC]
- ▷ New phases of matter; hadronic physics [heavy ions, ep, fixed-target]
- ▷ Exploration! [colliders, precision measurements, tabletop, . . .]
  Extra dimensions / new dynamics / SUSY / new forces & constituents
- ▷ Proton decay [underground]
- ▷ Composition of the universe [SN Ia, CMB, LSS, underground, colliders]

In a decade or two, we can hope to . . .

Understand electroweak symmetry breaking	Detect neutrinos from the universe
Observe the Higgs boson	Learn how to quantize gravity
Measure neutrino masses and mixings	Learn why empty space is nearly weightless
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)	Test the inflation hypothesis
Thoroughly explore CP violation in B decays	Understand discrete symmetry violation
Exploit rare decays (K, D, . . .)	Resolve the hierarchy problem
Observe neutron EDM, pursue electron EDM	Discover new gauge forces
Use top as a tool	Directly detect dark-matter particles
Observe new phases of matter	Explore extra spatial dimensions
Understand hadron structure quantitatively	Understand the origin of large-scale structure
Uncover the full implications of QCD	Observe gravitational radiation
Observe proton decay	Solve the strong CP problem
Understand the baryon excess	Learn whether supersymmetry is TeV-scale
Catalogue matter and energy of the universe	Seek TeV-scale dynamical symmetry breaking
Measure dark energy equation of state	Search for new strong dynamics
Search for new macroscopic forces	Explain the highest-energy cosmic rays
Determine GUT symmetry	Formulate the problem of identity

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. . . learn the right questions to ask . . .

. . . and rewrite the textbooks!